CAN DYNAMIC TIRE FORCES BE USED AS A CRITERION OF PAVEMENT CONDITION

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by

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Joint Highway Research Project

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Technical Paper

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TO: K. B. Woods, Director
Joint Highway Research Project

October 31, 1963

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

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The attached technical paper entitled "Can Dynamic Tire Forces be Used as a Criterion of Pavement Condition" by B. E. Quinn, Professor of Mechanical Engineering, and C. C. Wilson, Graduate Assistant has been prepared as a part of the HPS funded investigation known as "Stresses and Deflections". The paper is proposed for presentation at the Annual Meeting of the Highway Research Board in Washington D. C. in January 1964 and for publication by that organization.

The final report on this project has not been submitted but approval for presentation and publication of this paper is requested. In the event approval of presentation has not been received by the date of the presentation, the presentation will include the statement that the ISHC and the BPR have not reviewed the paper.

The paper is presented to the Board for action.

Respectfully submitted,

Harold L. Michael

Harold L. Michael, Secretary

HLM:bc

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Technical Paper

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by

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Joint Highway Research Project

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B. E. Quinn and C. C. Wilson

INTRODUCTION

A vehicle moving over a perfectly smooth pavement will in general exert only the static wheel loadings upon the highway. Uneveness in the pavement profile will, however, induce vertical motion in the vehicle and this will produce fluctuating force components that will be superimposed upon the static wheel loads. These fluctuating force components are referred to in this paper as the dynamic tire forces. The question is raised as to whether or not they can serve as a criterion of pavement condition.

It is evident that the dynamic tire force is a criterion of the interaction between a vehicle and the pavement. On a perfectly smooth pavement the dynamic tire force would be zero, while on a rough pavement the force would be large. Unfortunately, however, this force is influenced by factors other than pavement roughness. The suspension characteristics of the vehicle are significant as well as the speed of the vehicle. It has been shown (1) that under certain conditions it is possible to induce either large or small dynamic forces by simply varying the speed of the vehicle. It is thus evident that if a comprehensive study is made of the dynamic tire force, the vehicle characteristics and the vehicle velocity must be considered along with the pavement profile. Conversely, if only the effect of pavement condition upon the dynamic tire force is to be studied, then tests must be made with the same vehicle at the same speed over different pavement sections. These factors were investigated in the test reported in this paper and the results gave rise to the possible use of dynamic force as a criterion of pavement condition.

The question can well be raised as to the effect of the dynamic tire forces on the highway. Under certain conditions these forces may be small relative to the static wheel loads and they are applied for a relatively short period of time at any one location on the highway. The response of the highway to these forces, however, has been a matter of interest to many investigators.

It is well to note that although only small deformations may occur in the highway at moderate distances from the point of application of a dynamic tire force, this force may not be insignificant as far as damage to the highway is concerned. High forces will result in high contact stresses, and rapid surface deterioration may result even though the interior structure of the highway may not be adversely affected by such a force. It is thus evident that the relationship between dynamic tire force and highway response is an important area for continued study.

In like manner, the question as to the effect of the dynamic tire forces upon the vehicle can also be raised. These forces will in general have large vertical components that will give rise to deformations of the tires of the vehicle. Depending upon the frequency with which these forces are applied, it is possible to have either large or small motions induced in the sprung mass (body) of the vehicle. If large body motions are induced the passengers may experience considerable discomfort. If very little body motion is induced the passengers may be unaware of the fact that large dynamic forces are acting upon the tires of the vehicle.

It is thus evident that passengers, riding in a vehicle, may be unaware of large forces that are generated between the pavement and the vehicle even though these forces may be causing damage to the pavement. These passengers may even be giving an excellent rating to the pavement at

the instant that damage is resulting from an unfavorable combination of pavement condition, vehicle velocity and vehicle suspension characteristics.

Is a pavement in satisfactory condition when it will induce large dynamic tire forces? Is a passenger capable of evaluating pavement conditions based solely upon the "ride" of the vehicle? Clearly the task of evaluating pavement condition is not an easy one!

In this investigation the dynamic tire force was measured continuously as a test vehicle moved along the pavement and the resulting force records were analyzed to obtain the root mean square value of the dynamic tire force. In certain cases the frequency of occurrence of certain magnitudes of the force was determined. The effects of vehicle velocity and tire inflation pressure upon the dynamic force were briefly investigated.

MEASUREMENT OF TIRE FORCE

The measurement of the dynamic tire forces has been of interest to many investigators. The Bureau of Public Roads conducted an investigation into this problem and described a system for measuring dynamic wheel reactions that utilized the fluctuating air pressure in a tire of a vehicle (2). The technique was further developed by the Michigan State Highway Department Laboratories in Lansing, Michigan. The force measuring system used to obtain the results described in this paper was virtually identical to that used in Michigan except for minor modifications. It is interesting to note that an extensive investigation into methods for measuring dynamic wheel forces is at present being conducted in Germany and is briefly described in reference (3).

The relationship between the dynamic tire force and the change in tire pressure is shown in Figure 1. The tire air pressure indicated by "p" is actually the change in the inflation pressure due to the motion of the vehicle on the highway. With this change in air pressure is an associated change in the force of the tire on the highway as indicated by "F". By monitoring the air pressure in a tire it is thus possible to measure the dynamic wheel forces that are superimposed upon the static wheel load.

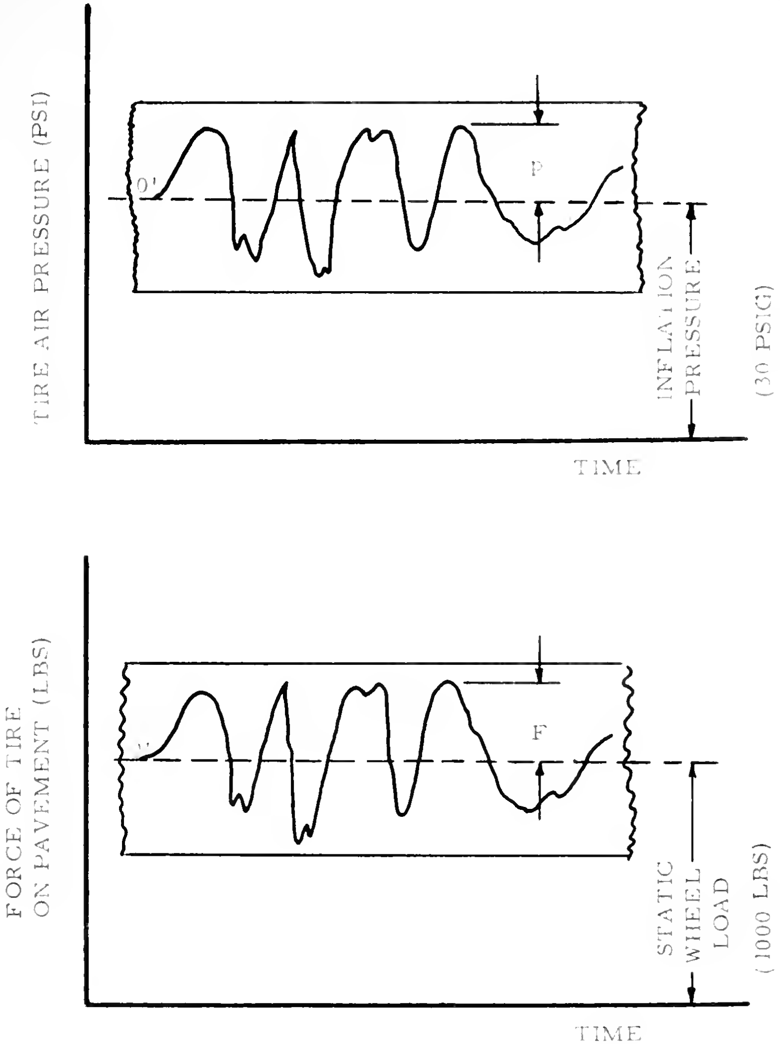

FIGURE 1 RELATIONSHIP BETWEEN TIRE AIR PRESSURE AND TIRE FORCE

In making tire pressure measurements, the valve core was removed from the valve stem of the tire and a short tube was connected from the valve stem to the rotating element of a special seal that was mounted on the wheel of the vehicle. From the stationary element of this seal, a tube was connected to the pressure measuring system shown schematically in Figure (2). By using this seal, it was thus possible to monitor the air pressure in a rotating tire.

A schematic diagram of the system for measuring the change in the air pressure in the tire is shown in Figure (2). Prior to making the measurements, the valve to the reference pressure tank was opened thus establishing the static tire pressure in all parts of the pressure measuring system. In taking the pressure measurements the valve was closed, thus subjecting side A of the differential pressure transducer to the fluctuating pressure in the tire while at the same time subjecting side B to the original tire pressure established in the reference pressure tank. As the vehicle moved down the highway, the pressure transducer responded to the difference in pressure between these two values and transmitted this information in the form of an electrical signal to an appropriate electronic circuit in which the signal was amplified and recorded with an oscillograph.

Certain difficulties are encountered in making measurements with this system. Air pressure in a tire is sensitive to temperature, and any heating or cooling of the tire will produce a difference in pressure relative to the original tire pressure introduced into the reference tank. In addition, small leaks will also cause a differential pressure to exist even though the vehicle may not be in motion. As a consequence, it is evident that undesirable factors may influence the dynamic tire pressure measurements when using the system just described.

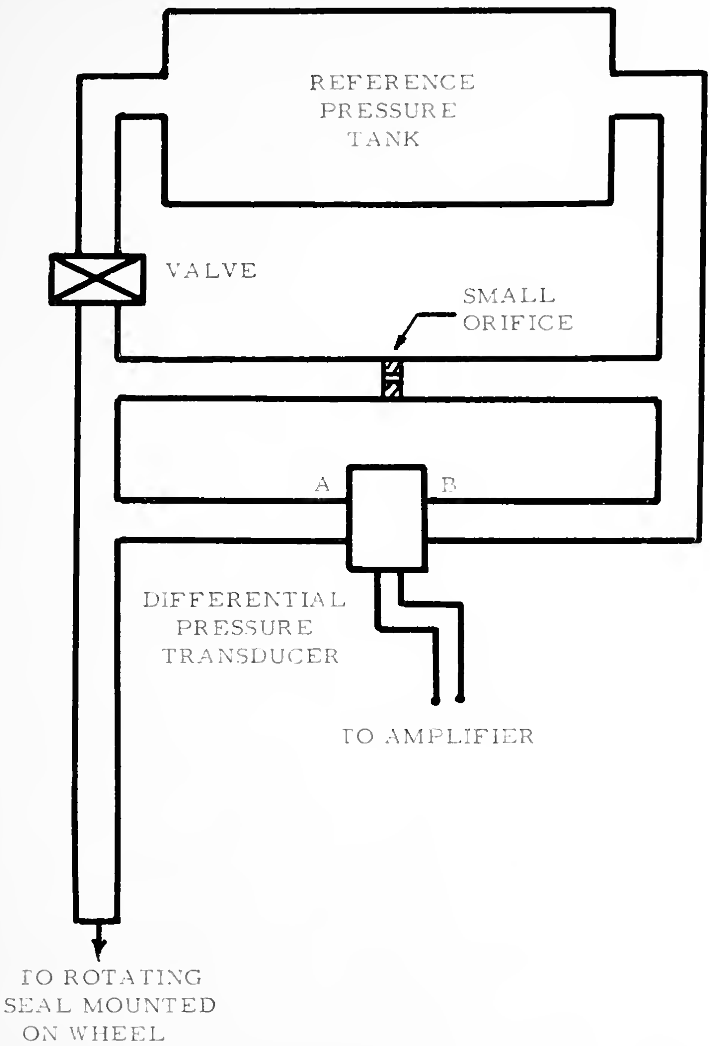

FIGURE 2 SCHEMATIC DIAGRAM OF SYSTEM FOR MEASURING CHANGE IN TIRE AIR PRESSURE

Relatively slow changes in tire pressure can be eliminated by the introduction of an appropriately selected orifice as shown by the dotted line in Figure (2). With this modification the effect of heating may be minimized, but the selection of the proper orifice requires care in order that no appreciable distortion of more rapid pressure changes will result.

It is also essential that the proper tube lengths and volumes be selected, otherwise resonances will occur due to the vibration of the air in the system. These vibrations will influence the differential pressure record and produce inaccuracies in the results. The factors that influence the behavior of this system are currently being studied, and detailed information concerning the design and behavior of this equipment will be available in a later report if there is sufficient interest.

Since it is necessary to convert fluctuating air pressure measurements to those of force acting upon the tread of the tire, an appropriate calibration relationship must be obtained. If the system is not carefully designed this relationship will vary considerably with frequency. Relationships between the dynamic tire force acting upon the tread of the tire and the change in air pressure as a function of frequency are shown in Figure 3. If inappropriate parameters are selected an undesirable relationship will be obtained as indicated. This characteristic, shown by the dotted line, indicates that the ratio of tire force to tire pressure varies with frequency. Thus at certain frequencies higher forces will result for the same change in tire pressure. This means that records taken in the time domain cannot easily be interpreted since different frequencies require different calibration factors in order to convert them to the appropriate value of tire force. The ideal characteristic is shown by the solid line in which the ratio of tire force to tire pressure is the same value at all frequencies. With this characteristic it is possible

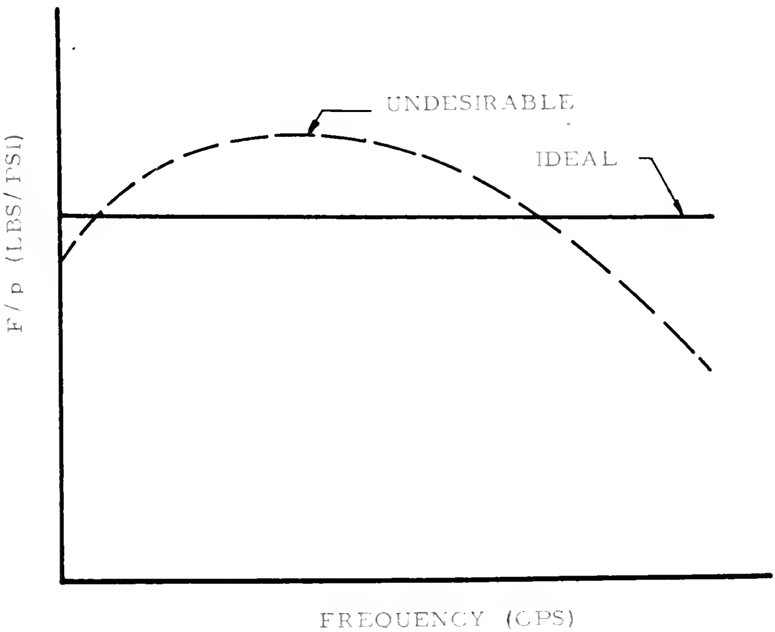

FIGURE 3 CALIBRATION CURVES FOR PRESSURE MEASURING SYSTEM

to take a time domain record, such as that shown in Figure 4, and to determine the force that will exist on the tire at a selected time regardless of the frequencies that exist in the record. It is thus evident that a calibration relationship shown by the solid line is most desirable, and hence the pressure measuring system shown in Figure 2 should be designed with this objective in mind.

The pressure measuring system was connected to the right front wheel of the test vehicle which was operated at a constant velocity over various sections of pavement. Knowing the velocity of the vehicle it is possible on the analog record to indicate the position of the vehicle on the highway and to determine the corresponding tire force. In making the actual record, it is necessary to switch on the electronic equipment and to approach the test section with the pressure measuring equipment in operation. In order to indicate the location on the record of the start of the test section, a special device is placed on the highway at the beginning and at the end of the selected section of pavement. When the tire of the test vehicle strikes this device, a special mark is made on the record thus establishing the beginning and the end of the pressure measurements relative to the highway.

Records thus obtained on the oscillograph are actually records of fluctuating tire pressure versus time. By using the vehicle velocity it is possible to convert time to position of vehicle on the test section, and by using the calibration curve it is possible to convert tire pressure to tire force. In order to obtain accurate records it is necessary to calibrate the test vehicle before any change in vehicle characteristics can occur between the time of calibration and the taking of the record.

This system for measuring dynamic tire force must be carefully designed so as to avoid spurious pressure fluctuations and to obtain a constant calibration relationship. When these conditions are realized, this system is very sensitive and will give consistent results.

ANALYSIS OF TIRE FORCE RECORDS

Oscillograph records of tire pressure versus time for two extremes of pavement condition are shown in Figure 4. The number o? on each record can be used to locate the records relative to the axes shown in Figure 1.

The ordinates representing change in air pressure can be converted to tire force if they are multiplied by the appropriate calibration factor previously mentioned. When this is done the force scale, shown at the left, can be added to each record. It is immediately evident that the difference in the smoothness of the two pavement sections has caused a large difference in the tire forces exerted by the wheel of the test vehicle upon the highway. In both cases the same vehicle was operated at the same speed, thus the difference is due to the condition of the pavement.

At the beginning of each test section a special mark was recorded. It is thus possible, knowing the vehicle velocity and the elapsed time, to indicate the distance traveled from the starting point by the distance scale shown on the record. The tire force at any location can thus be determined.

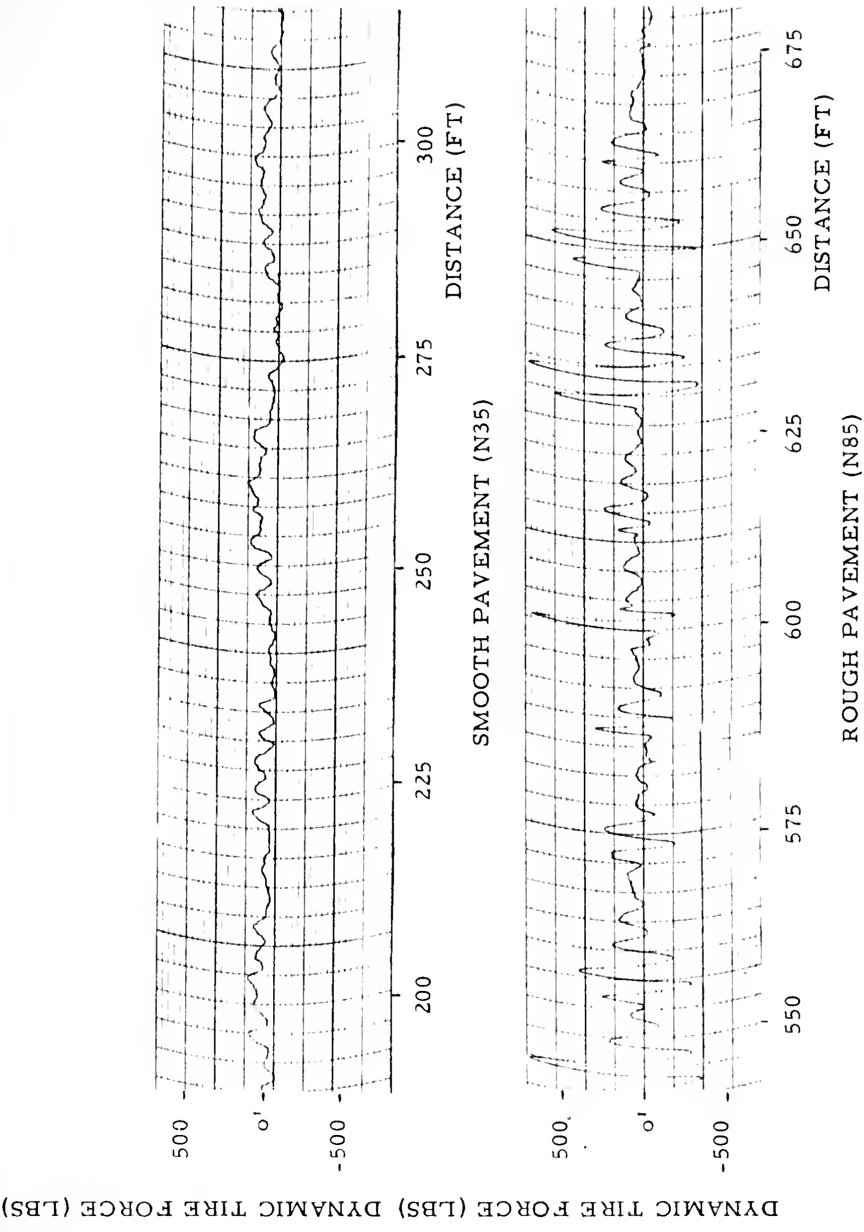

FIGURE 4 RECORDS OF DYNAMIC TIRE FORCE VERSUS DISTANCE FOR TWO DIFFERENT PAVEMENTS

Although the record for the smooth pavement shown in Figure 1 is useful in making a visual comparison of the two pavements in question, it is virtually useless for further study. It was thus necessary to obtain an additional record for which greater amplification in the recording equipment was used to obtain measurable results. This, however, changed the calibration factor for this record.

Having these records it is also possible to determine how often certain magnitudes of the dynamic tire force occur when driving over the pavement section. This can be done by first reading values of force from the record at equal intervals of distance. These are then assorted such that the number of values in various ranges of tire force is determined. This number is divided by the total number of force readings included in the analysis of the record to obtain the fraction of the values in the force interval under consideration.

Figure 5 indicates the results of this procedure when applied to the force records of which small sections are shown in Figure 4. The distribution of the dynamic forces in both records can thus be compared. It is interesting to observe that a much smaller increment of force must be used to study the distribution of the forces resulting from the smooth pavement than is used for the rough pavement, otherwise no meaningful distribution can be obtained. The pavements compared in Figure 5 are of different types of construction, and it is

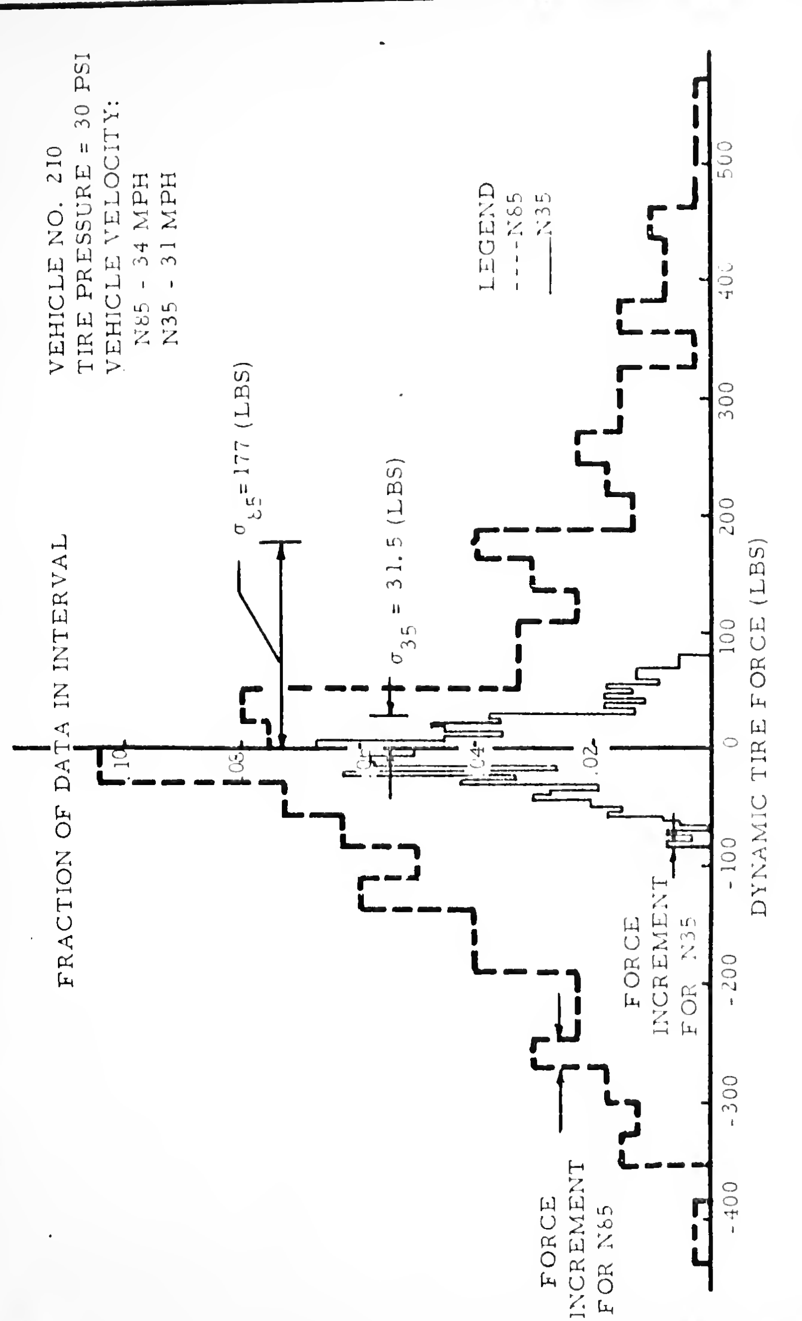

FIGURE 5 DISTRIBUTION OF DYNAMIC TIRE FORCES FOR PAVEMENT SECTIONS N35 AND N85

therefore interesting to compare pavements of the same type of construction but of different conditions of smoothness. Such a comparison is made in Figure 6 in which less striking differences are indicated.

It is evident from Figures 5 and 6 that the distribution of the dynamic tire force is not symmetrical. Larger positive tire forces are encountered than are those of negative sign. Since the positive values are added to the static wheel load to obtain the total tire force it is clear that the assumption of a symmetrical distribution will under-estimate the maximum forces that act on a highway. This possibility is investigated later in this paper.

It is, however, desirable to obtain a single summarizing statistic that can be used to describe the records in question. Since both positive and negative forces are encountered, an average value of force is not significant. A better criterion can be obtained by squaring each force value obtained from the record, obtaining the sum of these values, dividing this sum by the total number of data values and taking the square root of the quotient. This statistic is called the root mean square (RMS) values of the tire force.

This was done for force records taken on several pavements that varied in condition as well as in type of construction. The results of these calculations are shown in Figure 7. The RMS force values for each type of pavement construction are recorded and grouped as shown.

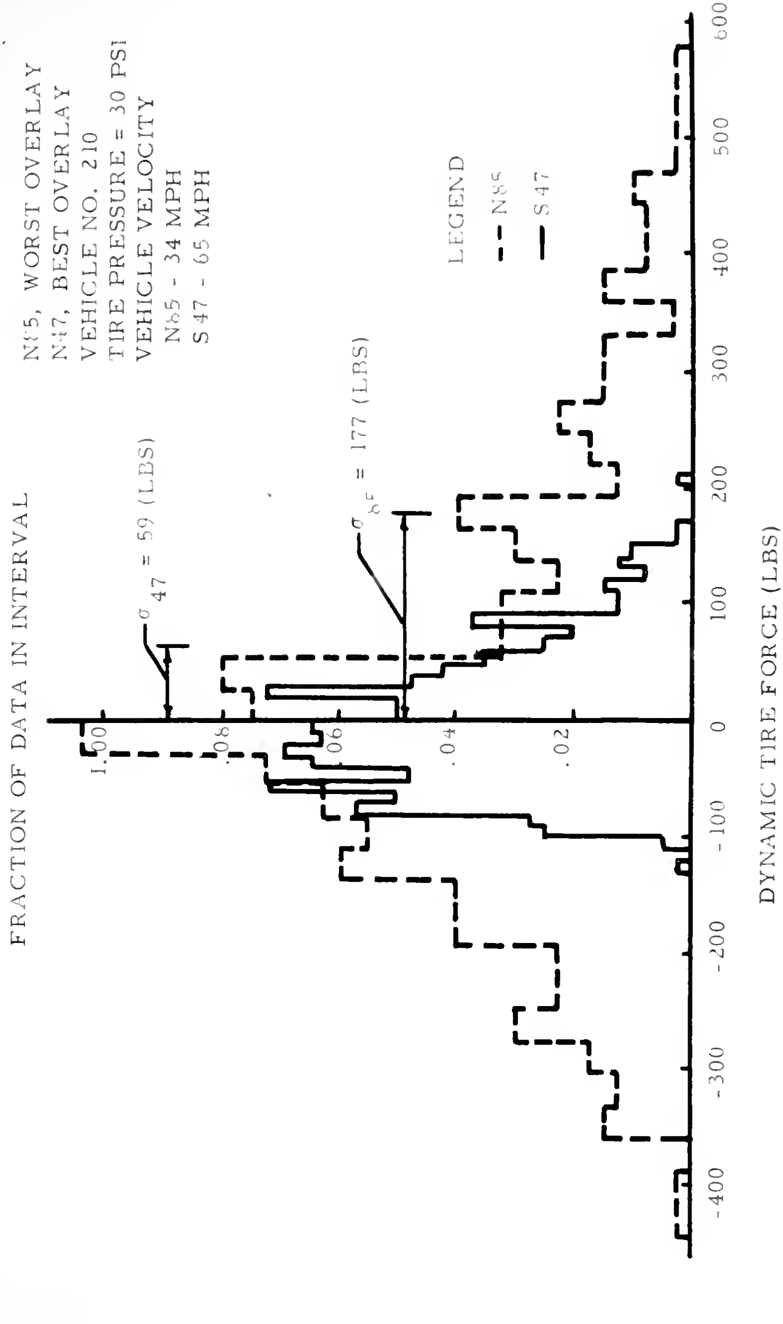

FIGURE 6 DISTRIBUTION OF DYNAMIC TIRE FORCES FOR PAVEMENT SECTIONS S 47 AND N85

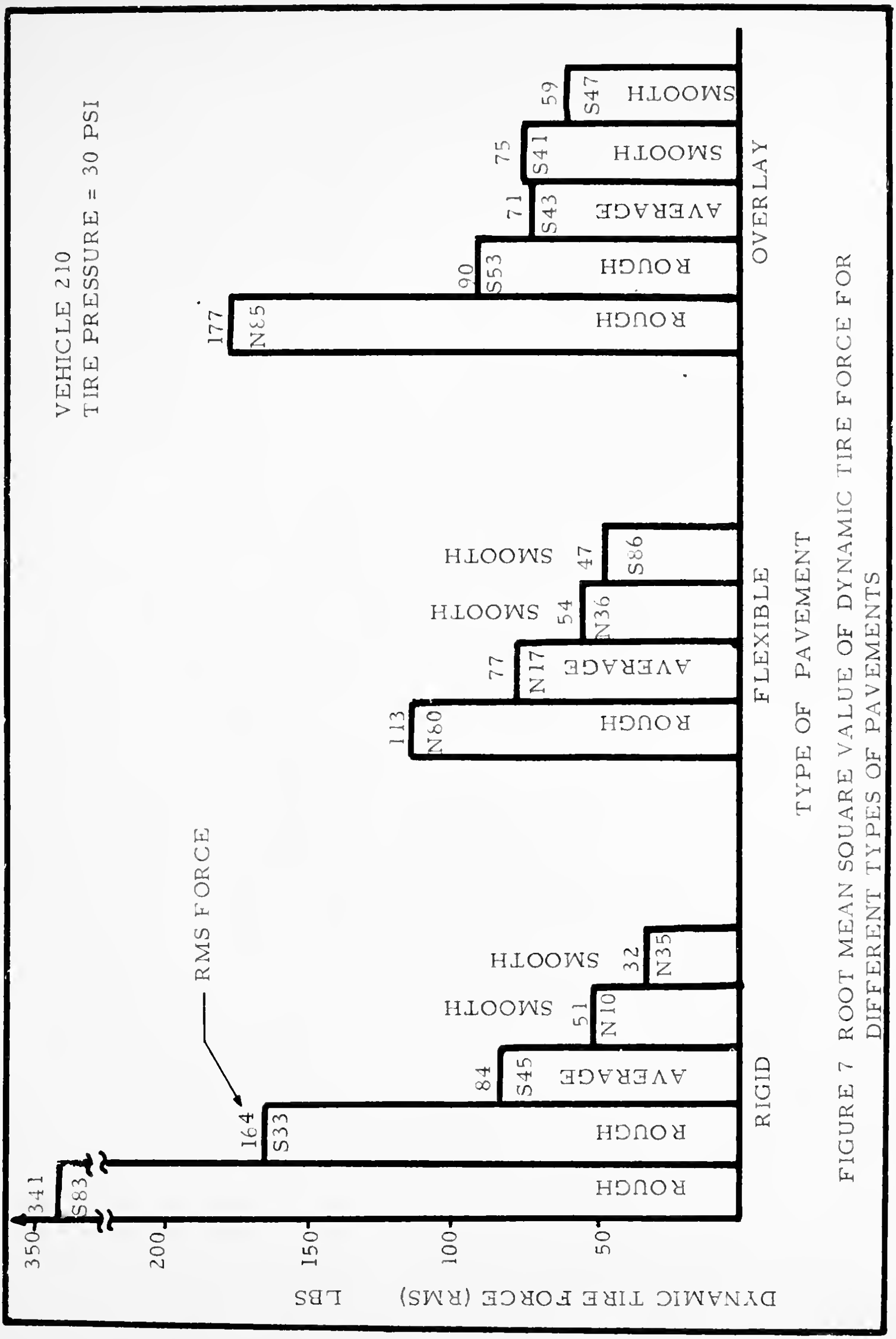

FIGURE 7 ROOT MEAN SQUARE VALUE OF DYNAMIC TIRE FORCE FOR DIFFERENT TYPES OF PAVEMENTS

In addition each pavement was assigned one of three subjective ratings (smooth, average, rough) as determined by the individuals who operated the test vehicle. It is interesting to note that RMS dynamic forces ranging from 32 lbs to 341 lbs were obtained. A large range of values is thus encountered when this statistic is employed as a criterion.

Although the subjective estimates of pavement condition are very crude, it is evident that low values of force are related to excellent pavement condition and that large values of force indicate that a considerable amount of roughness is present. Although a more extensive study of the correlation of dynamic tire force with pavement condition is necessary before final conclusions can be reached, it appears as if pavement roughness is related to dynamic tire force.

As mentioned previously, the velocity of the test vehicle influences the dynamic tire forces. This was investigated by operating the test vehicle over the same length of pavement at four different velocities. The resulting RMS values of tire force are plotted against vehicle velocity as shown in Figure 8. It is evident that under the conditions encountered in this test, the tire force increases with velocity. This has been predicted theoretically from highway and vehicle characteristics (4) (5).

Of some interest is the fact that the distribution of the dynamic tire forces changed with vehicle velocity as shown in Figure 9. As the speed increased the maximum force increased. In addition, the frequency of occurrence of the larger forces also increased. This was accompanied by a small decrease in the negative forces but with a much larger

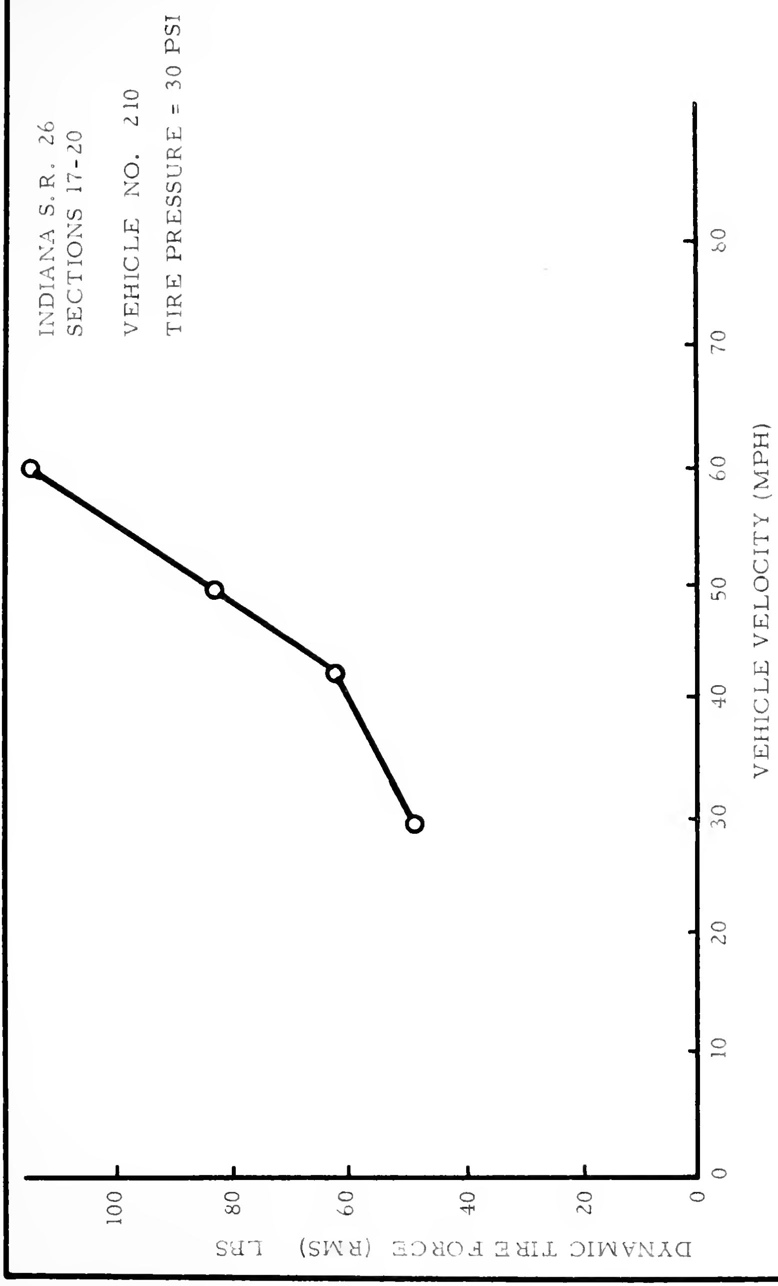

FIGURE 8 ROOT MEAN SQUARE VALUE OF DYNAMIC TIRE FORCE VERSUS VEHICLE VELOCITY

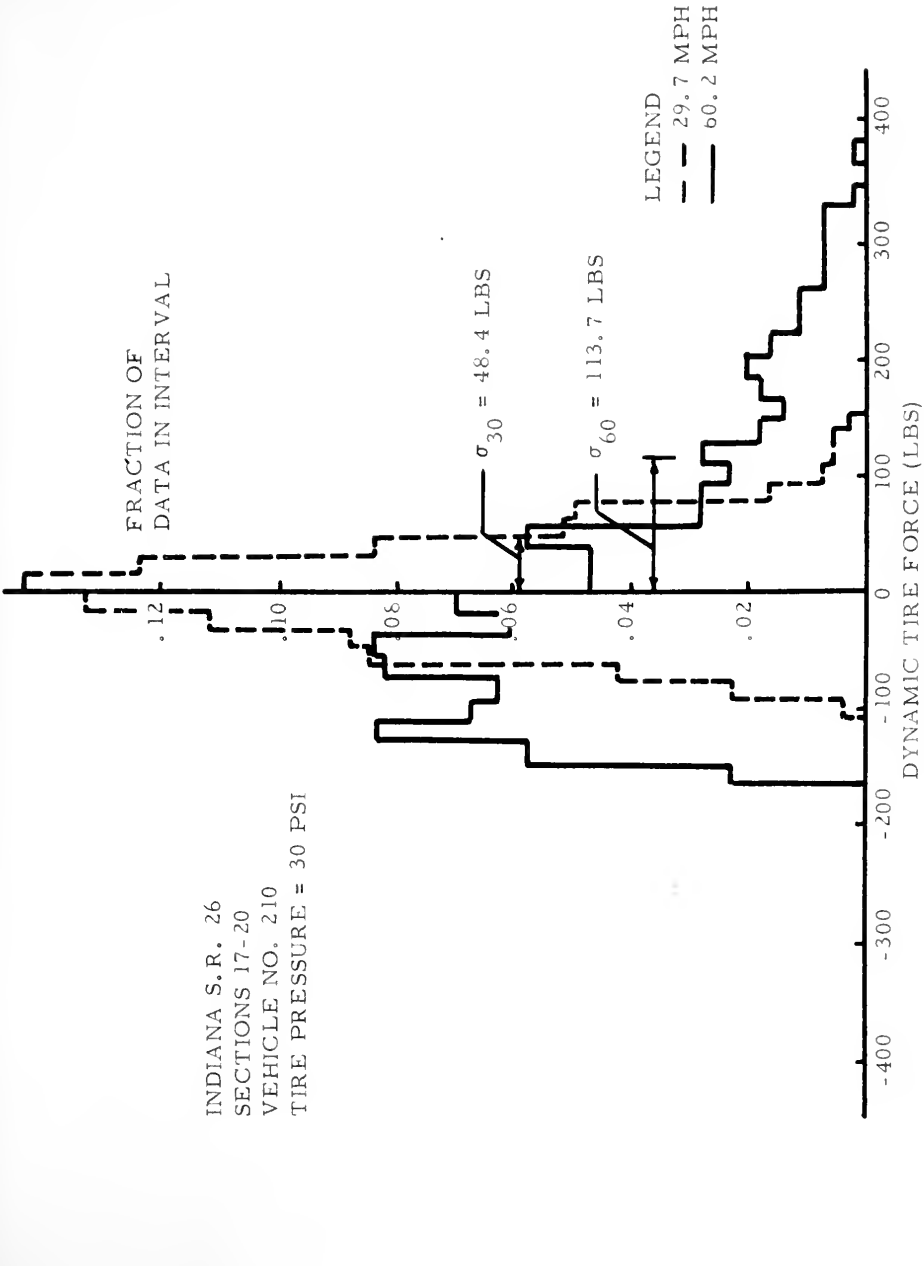

FIGURE 9 DISTRIBUTION OF DYNAMIC TIRE FORCES AT DIFFERENT SPEEDS

frequency of occurrence of the negative forces. In other words, the skewness of the distribution increased with vehicle velocity.

The dynamic force distribution shown in Figure 9 by the solid lines (60 mph vehicle speed) was obtained on a pavement typical of many in use today. Likewise, the test vehicle velocity was close to that of many of the vehicles now using this section of pavement. This distribution is therefore not an extreme case such as that shown in Figure 5, but can be considered as representative of frequently encountered conditions.

The distribution is highly skewed, and it is interesting to compare it with a normal distribution. Accordingly a histogram was constructed based on a normal distribution having the same mean and the same RMS value as the skewed distribution. The results are shown in Figure 10.

It is evident that the frequency of occurrence of large positive forces is underestimated by the assumption of normality, and that the range of the negative forces is overestimated. Depending upon the allowable error, the normal curve could be used as a first approximation for the positive forces. Since the positive forces are added to the static wheel load to obtain the total force of the tire on the road it is evident that the frequency of occurrence of those forces that may be quite significant in the life of a highway will be underestimated. This error appears small, however, for the data shown in Figure 10.

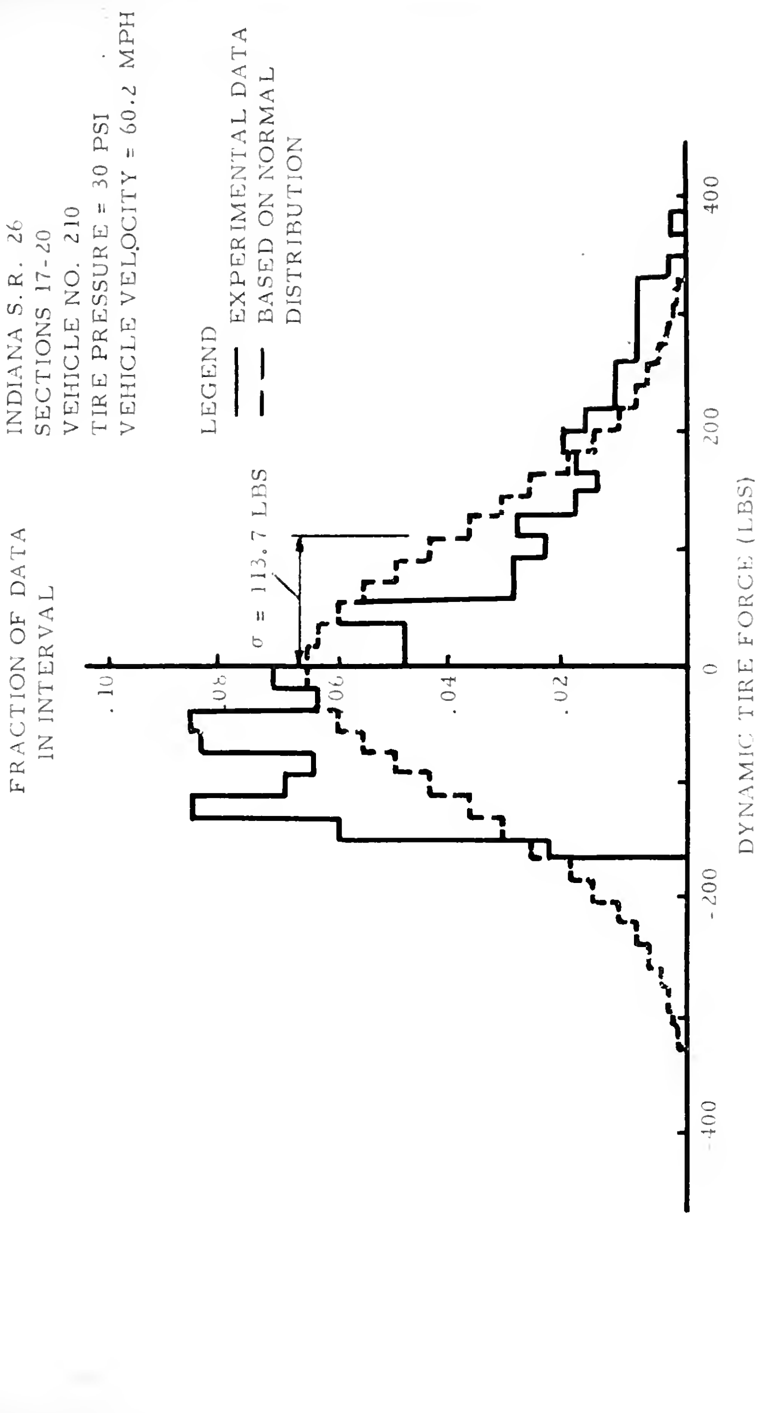

FIGURE 10 COMPARISON OF DYNAMIC TIRE FORCE DISTRIBUTIONS

Changing the inflation pressure in the tire will influence the dynamic tire forces. This was investigated by operating the test vehicle over the same section of pavement at the same velocity but with different tire inflation pressures. The results of this investigation are shown in Figure 11, in which the root mean square value of the dynamic tire force is plotted against tire inflation pressure.

Unfortunately tests were not conducted at relatively low inflation pressures and therefore this series of tests must be considered as incomplete. The curve indicates that low inflation pressures will result in lower tire forces, other factors remaining the same. Previous research (4) in this area indicated that a rapid drop in tire force could be expected for tire inflation pressures less than those recommended by the tire manufacturers. No such condition is shown in Figure 11 since all tests were conducted above the recommended pressure.

At high inflation pressures the calibration curve for the pressure measuring system approached that indicated as "undesirable" in Figure 3. A more accurate estimate of the RMS tire force requires a transformation in the frequency domain, and the procedure for determining force scales, described in connection with Figure 4, is no longer valid. It is therefore believed that an appreciable reduction in force will result from decreased inflation pressures, even though this is not indicated in Figure 11.

Vehicle characteristics influence the dynamic tire force records and it is appropriate to consider briefly this relationship. The pavement

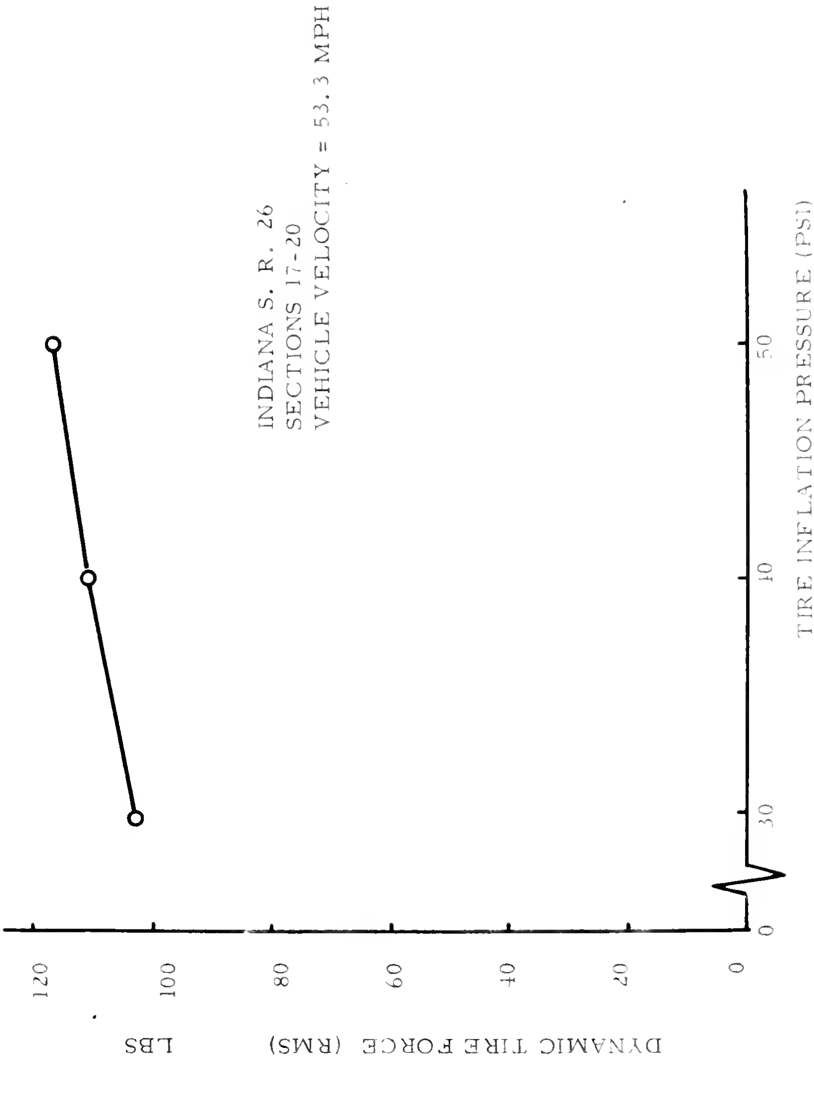

FIGURE 11 DYNAMIC TIRE FORCE VERSUS TIRE INFLATION PRESSURE

will excite vertical motion in the suspension system of the vehicle that will consist largely of the natural frequencies of this system. This motion will, of course, be reflected in the tire pressure measurements.

A study of the frequencies in a tire force record can be made by using a power spectral density analysis (6). Although it is inappropriate to discuss the details of this procedure in this paper, a brief description of the results of such an analysis can be given. The analysis yields a curve, plotted as a function of frequency, the area under which gives the mean square value of the tire force. In addition, the area bounded by any two ordinates gives the contribution to the mean square value that is made by those frequencies lying within the two ordinates.

This analysis can be useful in studying the force records used to obtain the distributions shown in Figure 9. The dynamic forde power spectrum for the test vehicle traveling at 30 mph is shown by the dotted line in Figure 12. Two peaks of appreciable magnitude are indicated by this curve. The first peak, occurring over a range of low frequencies, indicates that the motion of the sprung mass (body roll) of the vehicle makes an appreciable contribution to the total mean square value of the dynamic tire force. A second peak, occurring over a range of higher frequencies, indicates the contribution to this value that results from motion of the unsprung mass of the vehicle (wheel hop).

The power spectral density function of the dynamic tire force for the same vehicle traveling over the same section of pavement at 60 mph

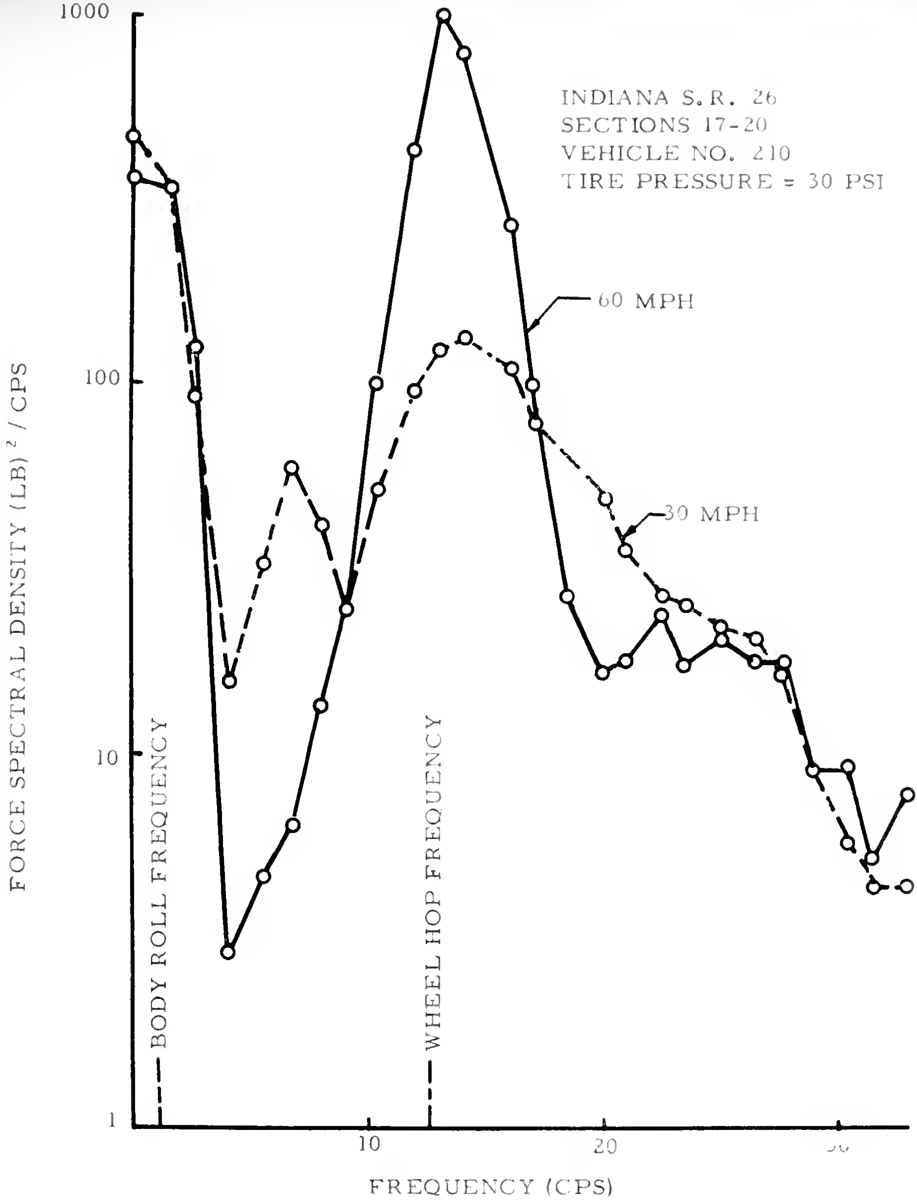

FIGURE 12 POWER SPECTRAL DENSITY ANALYSIS OF DYNAMIC TIRE FORCE RECORDS

is shown by the solid line in Figure 12. It is evident that the area under this curve is greater, indicating the higher mean square force as shown in Figure 8.

Of considerable interest is the change in the shape of the curve. The peak associated with the low frequencies is almost the same at both speeds, indicating that the motion of the sprung mass (body roll) did not change appreciably. The motion of the unsprung mass (wheel hop) was drastically increased at the higher vehicle speed as evidenced by the large increase in the ordinates of the curve in the region of the wheel hop frequency.

Another change of considerable interest is also evident. In the power spectrum curve for 30 mph, a small intermediate peak can be seen approximately midway between the two large peaks. This is due to a large amount of excitation coming from the pavement since no natural frequencies exist in the suspension system of the test vehicle at this frequency. When the vehicle speed is doubled the frequency of excitation from the highway is doubled. At 60 mph the excitation that caused the small intermediate peak has doubled in frequency, causing an additional excitation at the wheel hop frequency. Since the vehicle is very responsive at this frequency, a great increase in tire force is produced as shown by the curve.

SUMMARY

Several techniques have been discussed that are helpful in studying dynamic tire force records. The most useful single statistic appears to be the root mean square value of the force. This quantity can be used as a convenient summarization of a record and hence as a measure of the tire forces encountered for a selected pavement, vehicle and vehicle velocity.

Moreover, this quantity can be used to obtain a first approximation for the frequency of occurrence of various magnitudes of the total tire force exerted on the pavement. This can be done by using the static wheel load as the mean value of the total force, by assuming a normal distribution of the dynamic tire forces, and by using the root mean square value of the dynamic tire force as the standard deviation of the distribution curve.

The force power spectrum, Figure 12, indicates the extent to which various frequencies of vibration are present in the tire force records. Of greater importance, however, is the usefulness of this characteristic in performing operations in the frequency domain that can not be performed readily in the time domain.

CONCLUSIONS

It has been shown that the dynamic tire force is related to pavement condition. Rough pavements cause large forces and smooth pavements cause relatively small forces. If the matter is pursued no further, the use of tire force as a criterion of pavement condition is very simple.

Unfortunately other aspects of the relationship between tire force and pavement condition must be considered. Confusion is introduced when different tire forces can be obtained on the same pavement by simply varying the speed of the vehicle. Can any pavement be rated as either good or bad, depending upon the speed selected to take the tire force records? Can the rating of a pavement be changed from bad to good by simply changing the inflation pressure in the tires of the vehicle? Tire force as a pavement condition criterion is susceptible to these manipulations.

It is important at this point to inquire as to the actual significance of a pavement condition criterion. Is it solely a measure of the geometric properties of a pavement? If so, dynamic tire force measurements are unsatisfactory.

For what purpose is a pavement constructed? Is it not intended to serve vehicular traffic? Is it then unreasonable to use as a pavement condition criterion a measurement that is sensitive to the behavior of the vehicle on the highway?

Actually the dynamic tire force is a criterion of a combination of factors that includes pavement condition. Thus the forces that are exerted against the pavement can be influenced by the vehicle suspension system and the speed of the vehicle. These forces can be decreased, if necessary, by modifying the vehicle and by changing the operating conditions. It is thus apparent that different vehicles, moving with different velocities, will each respond in a different manner to the same highway.

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